

EUREX D

An Expert System for Failure Diagnosis and Recovery
in the TCS of the European Retrievable Carrier
EURECA

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ABSTRACT

In this paper an expert system for diagnosis and recovery of failures in the freon cooling loop of the European retrievable experiment carrier EURECA is described. This system demonstrates the feasibility of a functional scope of expert diagnostic systems which appears to be essential for practical applications of such systems in space technology. This scope comprises : early warning and treatment of incomplete information, fault tolerance, identification of failure superpositions (particularly involving failed sensors), intelligent reaction to unforeseen events and detailed status display for optimal recovery action.

1. INTRODUCTION

Particularly in view of the implementation of expert systems for failure diagnosis and recovery on autonomous spacecraft, but also with respect to their application as ground-based consultant systems, a certain enhanced functionality of such systems appears to be essential, covering in particular early warning and treatment of incomplete information, failure superposition, intelligent reaction to unforeseen events, tolerance to isolated faults in the knowledge base and detailed status display for optimal recovery action.

In this paper an expert system is described which, in its first development phase, has been used to implement and assess the technology required for the realization of these requirements for the diagnostic process. As such it could initially be used as a ground-based operator's consulting system, serving at the same time as test-bed for a further refinement of this technology for subsequent on-board applications.

2. THE COOLING LOOP OF EURECA

As system to be monitored the cooling loop of EURECA was chosen with the aim of a later expansion of the knowledge base to also include the thermal control unit, thus providing the complete TCS as application domain in the final stage.

The cooling loop of EURECA is depicted in Figure 2 showing the pump package (FPP) consisting of two redundant pumps of which one drives the cooling medium, freon, through the experiment line (upper branch) where the freon cools the experiments, then through the two radiators (Rad +x and Rad -x) where the heat taken up by the freon is dissipated and finally through the equipment line (lower branch) where equipment such as batteries and power distribution units are kept approximately at room temperature.

The fine tuning of the freon temperature is achieved by small adaptive heaters positioned along the experiment and equipment line as well as on the radiators.

The sensors are shown as icons in Figure 2 and measure pump inlet pressure (P_{in}), pump outlet pressure (P_{out}), pump inlet temperature (T_{in}), radiator inlet temperature (T_{s_3}), radiator outlet temperature ($T_{s_{1,2}}$), freon quantity in the accumulator (Acc. Q.) and the electrical pump current (I_p). Moreover, a delta pressure switch (dP) gives a signal if the pump pressure head has

broken down. (It should be mentioned that the question whether all these sensors will be available for EURECA is still under discussion. However, as the initial development stage of the expert system only aims at a technology demonstration, the exact number and type of sensors used is not crucial).

In addition to these direct measurements, the total power consumed by the adaptive heaters for the experiment line (Pwr Ex), the radiators (Pwr +x and -x) and the equipment (Pwr Eq) is also used, since changes in this power can serve as indirect indications of changes in flow, thus substituting to a certain extent the fact that a direct flow measurement will not be available for the EURECA cooling loop.

3. KNOWLEDGE REPRESENTATION

EUREX D has a rule-based knowledge representation which is characterized by :

- o **Global monitoring :**

Diagnosis is not only based on single sensor monitoring but on a global assessment of the concurrent readings of all sensors, identifying characteristic data patterns and relations (such as temperature gradients along the different sections of the cooling loop) thus providing a broad basis for the diagnostic process.

- o **Indirect monitoring :**

Apart from a direct interpretation of sensor signals such as interpreting the activation of the delta pressure switch as pump performance degradation, extensive use is made of indirect monitoring such as taking a flow reduction as additional evidence for the pump performance degradation, or using temperature readings for a measurement of flow as indicated above, etc.

- o **Redundant monitoring :**

In the reasoning process ALL known evidence for a given anomaly is taken into account thus allowing for incomplete or even partially erroneous information or knowledge to be processed without grave consequences since the system's dependency on individual bits of information or knowledge is greatly reduced.

- o **Multi-valued logic :**

Taking all known evidence into account implies the use of non-conclusive evidence :
For instance, the flow reduction mentioned above as being indicative of a pump performance degradation could also indicate a flow blockage or even a superposition of both anomalies.
Therefore rules generally hold only partially, which is represented by implication strengths σ taking values between 0 and 1, assigned to the rules.

- o **Causal connectivity :**

Although EUREX D does not reason "from first principles" but relies on knowledge based on engineering experience and heuristics, it is able to identify causal connections between states (e.g. a flow blockage being the cause of a flow reduction) for greater transparency and completeness in the description of the system's state. The knowledge necessary to identify these causal connections is provided by pointers assigned to the states.

4. INFERENCE MECHANISM

The various steps in the knowledge-based data processing, which are also reflected in the system's architecture shown in Figure 1, are given by :

- o **Data processing :**

i.e. the computation of temperature gradients along the various sections of the cooling loop, pressure differences etc.

- o **Data classification :**
i.e. local classification of the data in relation to the nominal interval generating "observations" such as "temperature high", "pressure normal" etc.
- o **Sensor state assessment :**
Dedicated rules check the plausibility of sensor readings on the basis of these observations and assign belief values to the sensors : 1 for normal operation, 0 for degraded sensors.
- o **System state assessment :**
For each system state, all rules pointing to this state are "tickled" and the implication strengths of fired rules are collected by an accumulation function leading to an integrated certainty factor. In the case of several inference steps (where system states serve as evidence for other system states) composite implication strengths are computed by propagation functions. In particular sensor belief values of 0 simply cause any inference based on this sensor to drop out of the reasoning process.
- o **State evaluation :**
States with certainty factor 1 are displayed as diagnoses. In case such cannot be found, several states with the highest certainty factors are presented as possible but not conclusive diagnosis. Diagnosed states are displayed in columns, the states given in a certain column always being the cause of the states in the adjacent columns to the left, thus generating a detailed status display which is not just based on the primary cause of an anomaly.
- o **Recovery actions :**
Depending on the diagnosis, appropriate recovery actions are selected. When the diagnosis is not conclusive, i.e. when it consists of several states with certainty factors less than one, the suggestions for recovery actions obviously also cannot be conclusive but are qualified by priority factors which are functions of the certainty factors and possible additional information (such as the rule to always react to the most hazardous situation first, even if it has a comparatively low certainty factor). However, this identification of recovery actions has not yet been implemented in EUREX D.

5. IMPLEMENTATION

EUREX D is being developed on the LISP-based development environment KEE and runs on SYMBOLICS machines.

Sensor-dedicated demons are responsible for the data classification described above. States are objects (units in KEE terminology) automatically collecting the evidence pointing to the states and computing the integrated certainty factors. Rules are grouped into classes corresponding to their firing priority in the inference process. Based on KEE's facilities the man-machine interface is strongly supported graphically, facilitating knowledge acquisition and explanation of the reasoning processes. In particular, the sensor readings are shown as bar graphs and their classification as shaded/non-shaded areas, responding actively to the input data. Conversely, the bar graphs can be mouse-manipulated to preset the sensor readings for an initial nominal and a final anomalous state for an in-built test simulator. This simulator generates, at fixed time intervals Δt , the sensor readings of the intermediate states which develop as the anomaly evolves from the initial nominal state to the preset end-state.

At each Δt EUREX D then performs its diagnosis on the sensor readings of these intermediate states.

6. FUNCTIONAL SCOPE

EUREX D displays the following functional scope corresponding to the requirements listed in the introduction :

- o **Early warning and treatment of incomplete information :**

Due to this fact that the reasoning mechanism is based on multi-valued logic and can process non-conclusive evidence, the system does not depend on the sensor data patterns characteristic of fully evolved anomalies for its diagnosis, but is able to process first symptoms of developing failures (i.e. incomplete information), presenting assumptions of several possible failures (weighted with certainty factors less than 1) for early warning and preventive action. An example of an assessment of the evolving symptoms of a flow blockage is given in Figures 2-3. A similar treatment applies when the incompleteness of information is due to other reasons, such as reduced sensor availability etc.

- o **Failure superposition :**

Obviously a premeditation of all failure superpositions for a diagnostic system is impossible, and, like most other diagnostic systems, EUREX D is designed for the diagnosis of single failures only. However, it does display the ability to treat failure superpositions to a fair extent :

Degraded sensors are detected by dedicated sensor rules and taken out of the diagnostic process as described in Chapter 4. The diagnosis of simultaneously occurring system anomalies then proceeds on the basis of incomplete information as shown above. Thus concurrent sensor failures and system anomalies can be discerned.

Concurrent system anomalies can obviously be detected if they do not have opposing effects on the same sensors. Otherwise the system will again offer several assumptions with certainty factors less than 1. For example the superposition of a flow blockage and a leak leads to the assumption of pump performance degradation (c.f. = 0.5), leakage (c.f. = 0.7) and flow blockage (c.f. = 0.5).

- o **Treatment of unforeseen events :**

Processing of non-conclusive evidence in EUREX D also facilitates intelligent reaction to non-premeditated events. On the basis of the subset of recognized features, known situations are enumerated which have the greatest similarity to the unforeseen event.

At the same time, the fact that these are just assumptions is signalled by certainty factors less than 1.

- o **Tolerance to isolated faults in the knowledge-base :**

Regardless of whether such faults are due to erroneous coding or some irradiation of computer memory in case of on-board expert systems, it is imperative that an expert system does not react catastrophically in case of such error.

Due to the excessive knowledge redundancy (see chapter 3) this tolerance is indeed given to a great extent in EUREX D, where most isolated faults are "drowned" in the "majority vote" of the remaining evidence.

- o **Detailed status display :**

The inclusion of states causally connected to primary failure states for greater detail of status display has already been described in Chapters 3 and 4.

7. CONCLUSIONS

An expert system for the failure diagnosis of the cooling loop of EURECA has been described which displays a couple of features which appear to be essential for practical applications of such expert systems in space technology, the main aspects of the underlying methodology being given by knowledge redundancy and multi-valued logic.

It should be noted, however, that the management of uncertainty involved still poses some problems in the case of very large knowledge-bases and future work will have to concentrate on this aspect.

